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Intelligent Vehicle Mobility M&S Capability Development
(FY13 Innovation Project)

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19 May 2014

Report Documentation Page

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14. ABSTRACT
An integrated modeling and simulation capability for intelligent vehicles that can model desired mobility scenarios of interest, on-road or off-road, and is High fidelity Fast Scalable Flexible Adaptable Helps enhance mobility i.e., goes faster and farther

15. SUBJECT TERMS

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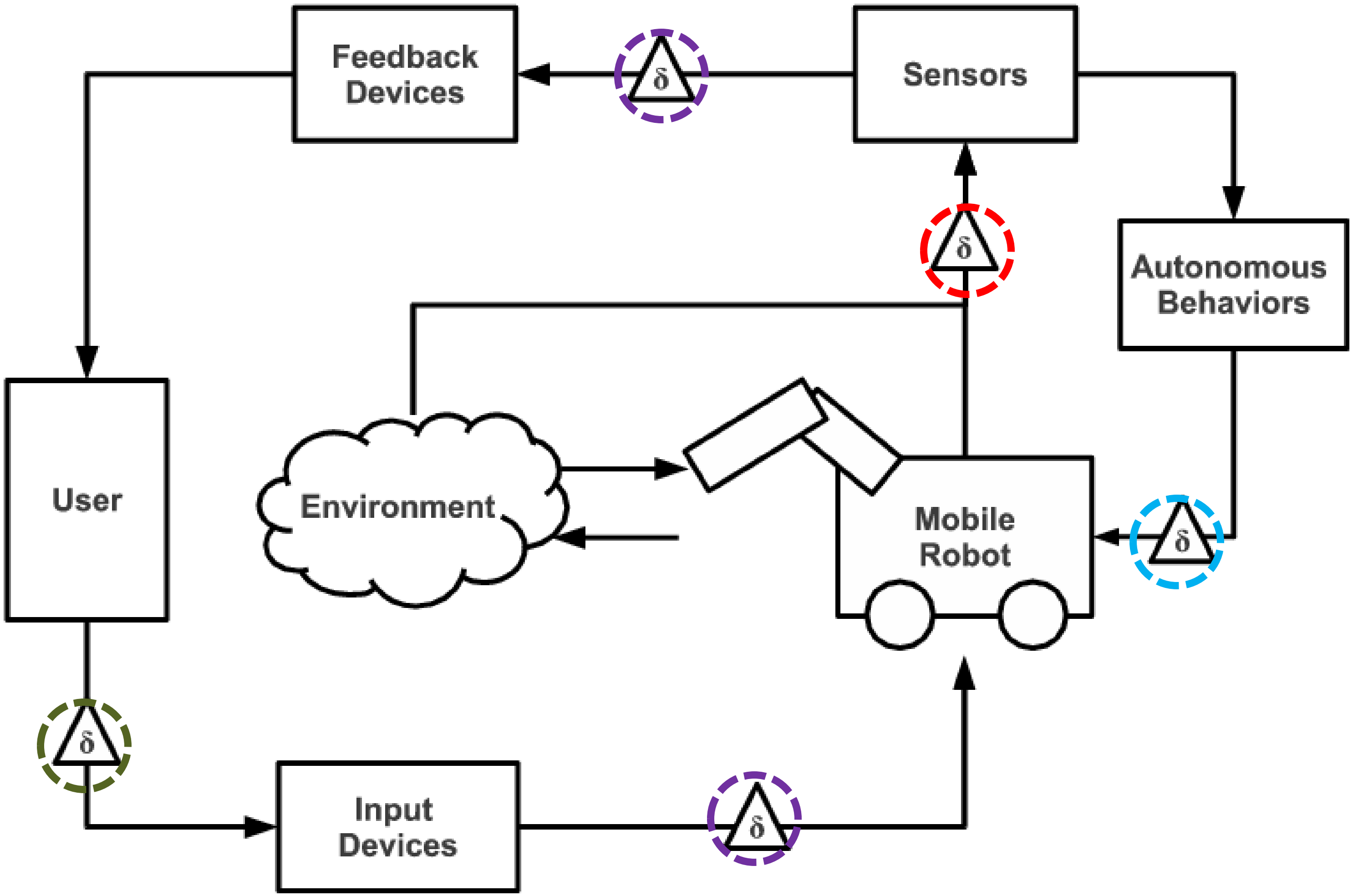
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Goals

- An integrated modeling and simulation capability for intelligent vehicles that can model desired mobility scenarios of interest, on-road or off-road, and is
  - High fidelity
  - Fast
  - Scalable
  - Flexible
  - Adaptable
  - Helps enhance mobility
    - i.e., goes faster and farther
- Funding: $50K

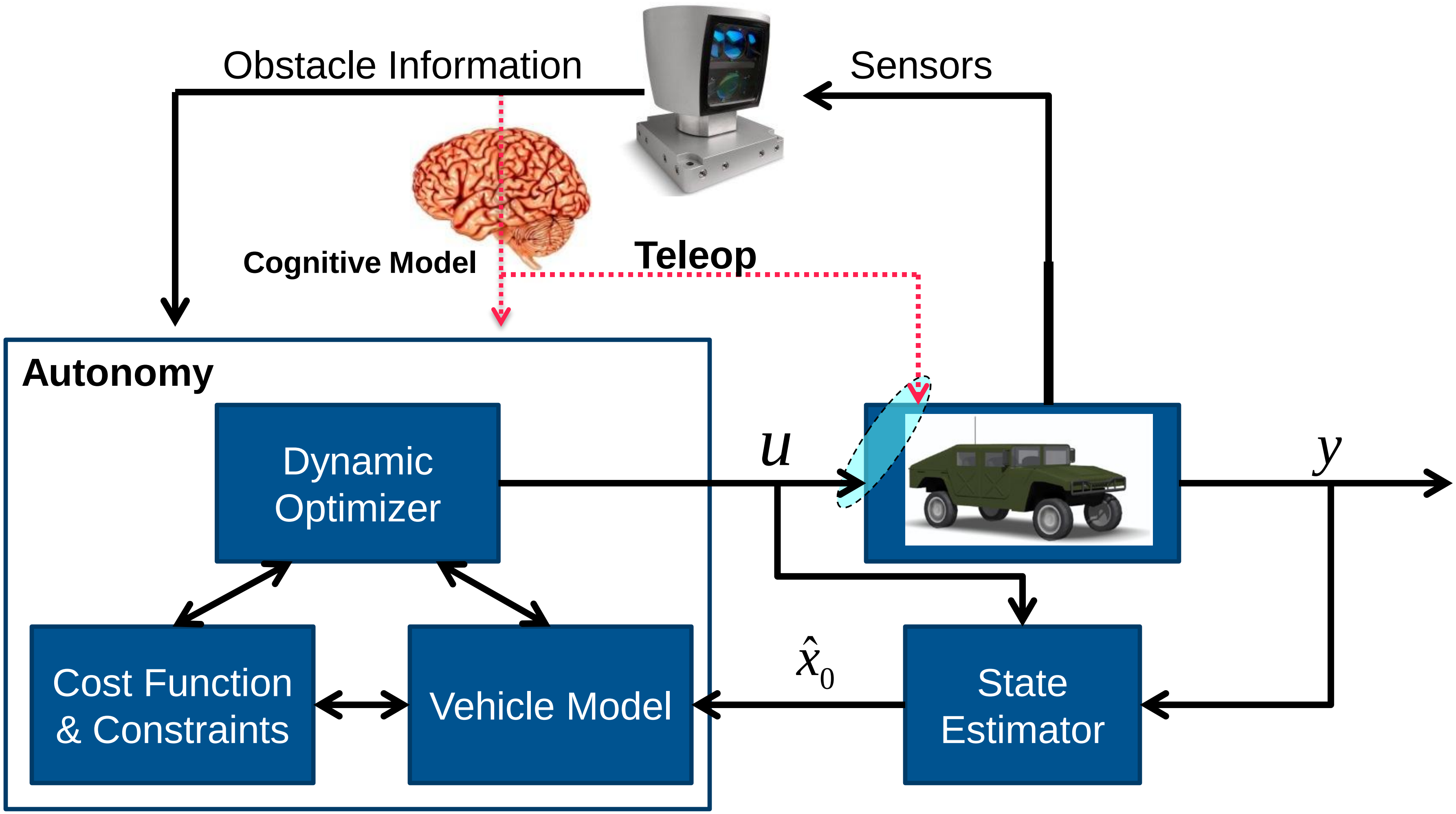
Teleop to Autonomous Robotics



Delays:
- Network
- Sensing
- Processing
- Operator

Vozar, S. and Tilbury, D. M., “A System-Level Methodology for Design Optimization of Teleoperated Mobile Robot Speeds,” ARC Project.

Teleop to Fully Autonomous Vehicle M&S



u : Control Signal: Steer Angle, Braking Pressure, Throttle Angle

KO: 1.1.1, 1.1.4

Model-Based Development of Mobility vs. Latency vs. Autonomy Relation

Platform Mobility (TARDEC)

- Mobility Scenarios Selection
- Mobility Metric Selection
- Dynamic Model Fidelity Decision 
- Dynamics Solver Selection
- Terramechanics Approach Development
- Compute Power Selection (ARL TPA)
- Simulate Mobility Events

Communication

- Communication Network Selection (OSD SBIR)
- Identify Delays and Bandwidth Issues
- Implement Delays
- Simulate Mobility Events for Various Delays (TARDEC)
- Analyze Effect of Delays
- Mitigate Effect of Delays

Autonomy

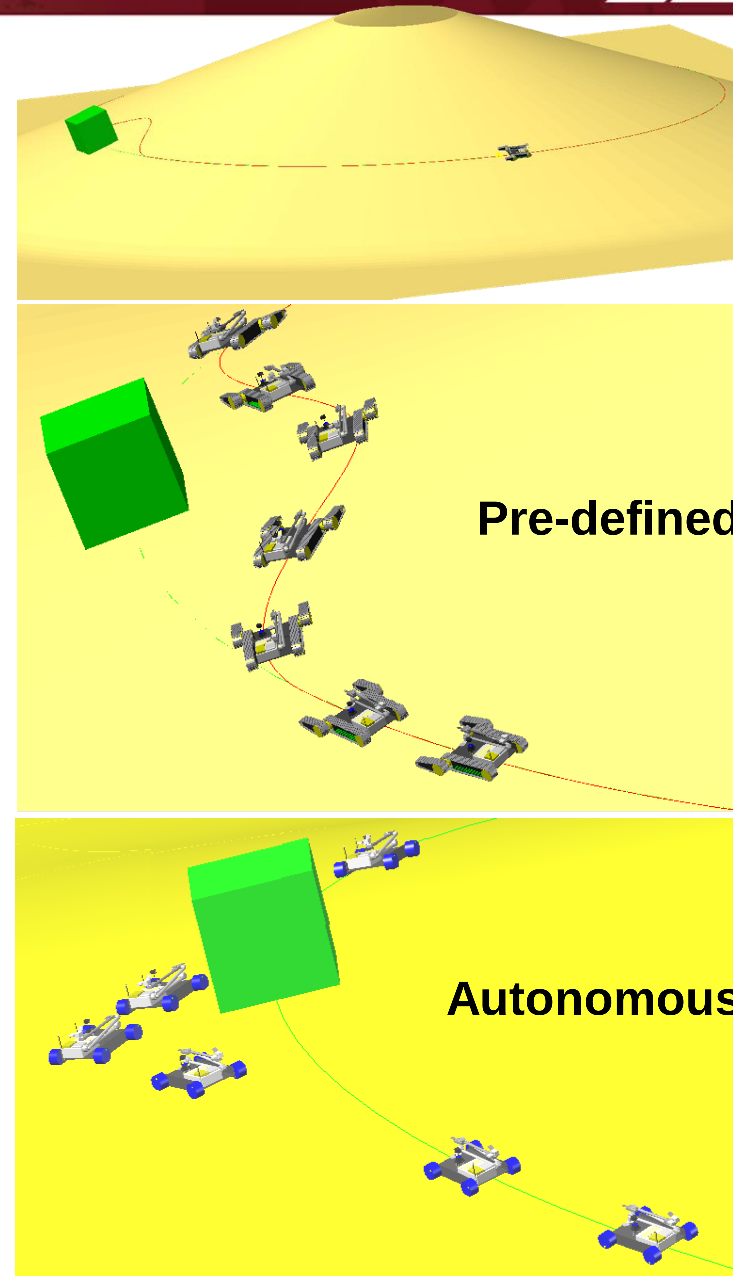
- Select Framework for Shared Control (MIT)
- Control Algorithm Selection (UM)
- User Cognitive Model Selection (TARDEC) 
- Sensor and Perception Algorithm Selection
- Identify Delays
- Simulate Mobility Events for Levels of Autonomy (TARDEC)
- Determine Autonomy & Latency Relationship to Maximize Mobility

Myth 1

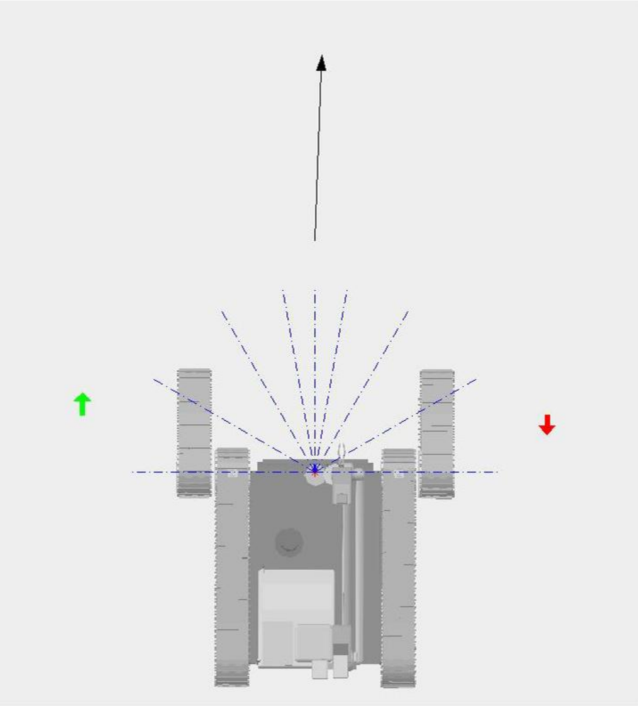
Vehicle mobility is mainly a function of the vehicle mechanical platform irrespective of whether manned or unmanned.

Pre-Defined Path vs. Autonomous

- **Predefined path**
  - Detailed track model
  - Predefined avoidance path
- **High-Fidelity**
  - Detailed track model
  - Autonomous operation
- **Simplified**
  - Simplified wheel model
  - Autonomous operation
- **Co-simulation of RecurDyn, PreScan, and Simulink**



Autonomous Operation



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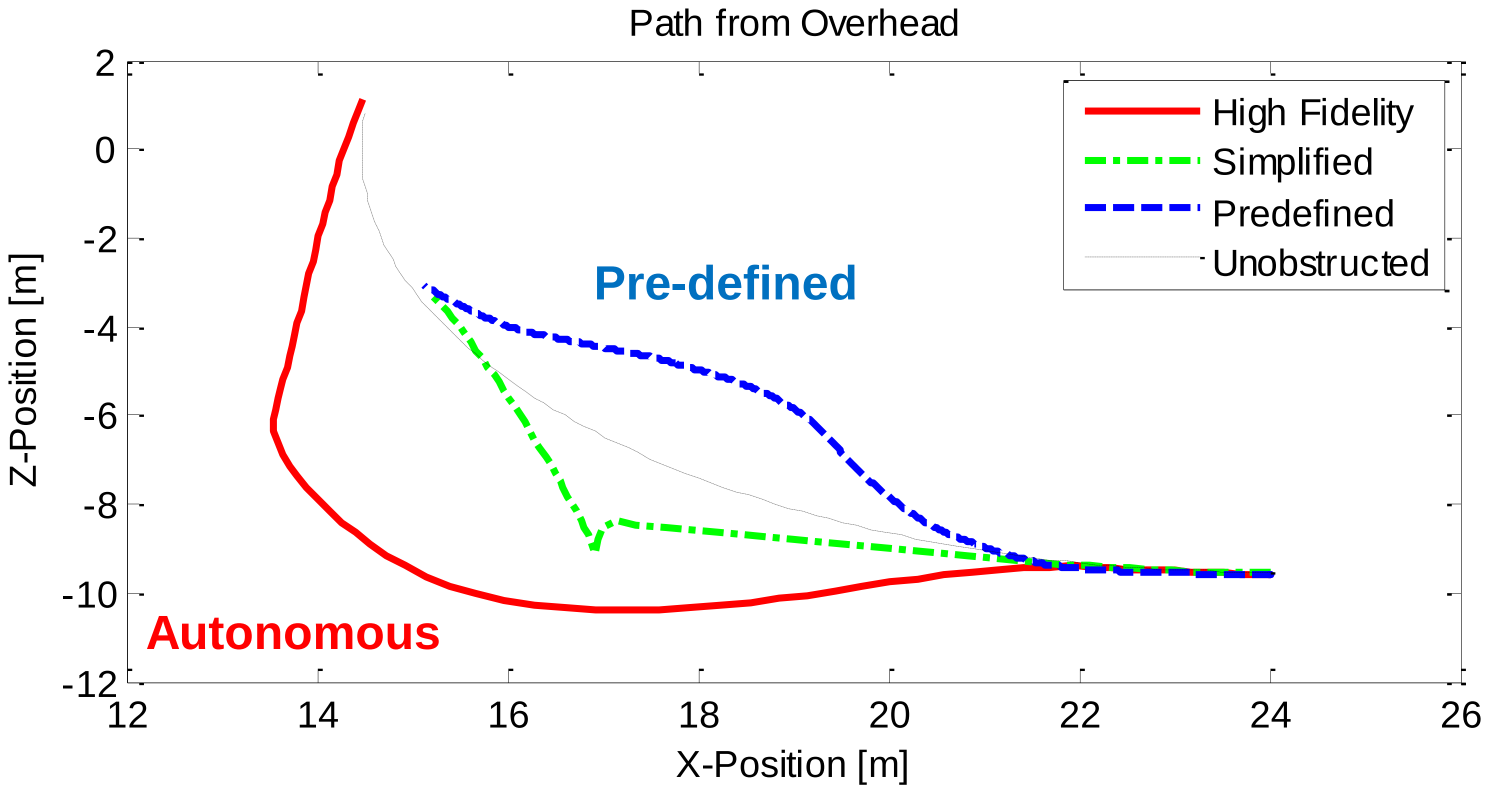
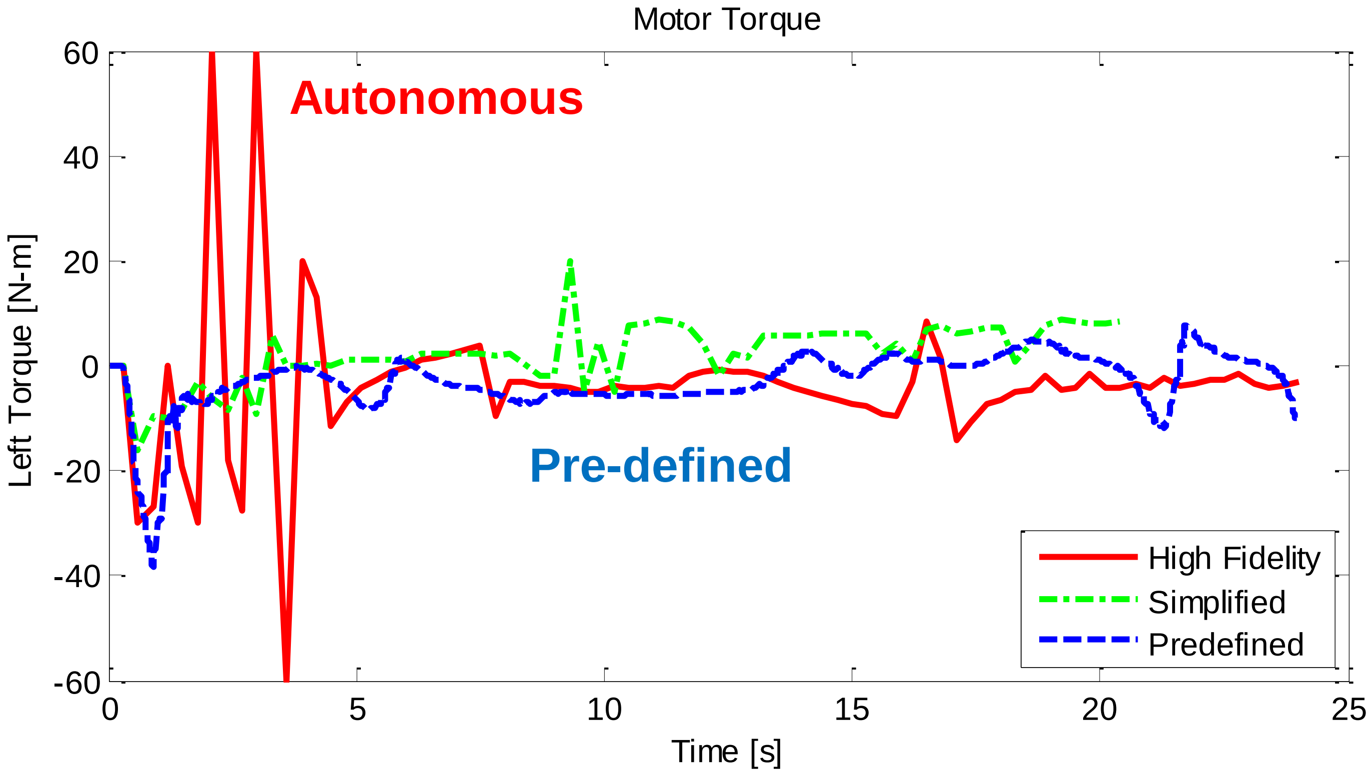
Simulation Comparison

- **Trajectory differences based on simulation type**



Simulation Comparison

- **Motor torque differences based on simulation type**



- **Average power requirements (W)**
  – **High Fidelity: 86.4** Simplified: 42.8 **Predefined: 27.6**

Myth 2

Robotic simulations look cool and realistic so they must be real.

Robotic Mobility M&S Tool Environment

Usage Rights	Commercial	Government Rights	Government Owned	Open Source
Program Classification / Sponsor	CML	ERDC[1], ARL[2], FCS[3]	SOURCE[1], NASA[2]	DARPA
PI / Organization	CML	QS[1], GDRS[2,3]	ERDC[1], JPL[2]	OSRF
Timeline	Exists	Exists	Exists	Exists
Program Information	VORTEX	ANVEL[1] RIVET[2] MODSIM[3]	VANE[1] ROAMS[2]	Gazebo

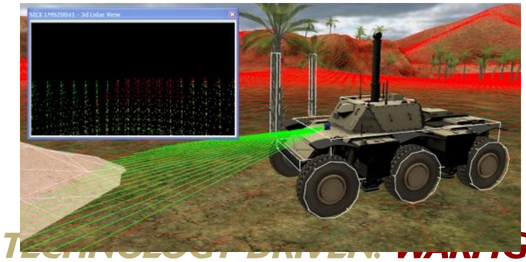
Autonomous Navigation Virtual Environment Laboratory (ANVEL)

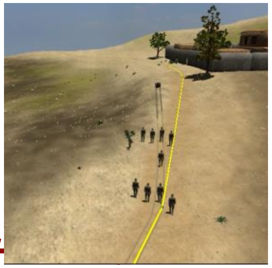
- **Developed for ERDC since 2007**
  - Original intent: real-time, desktop “front end” to support high-fidelity, off-line HPC-based simulations in VANE
  - Evolved into desktop UGV simulation package

- **Modular, flexible simulation tool and easy-to-use environment**
  - Real-time interactivity
  - Ability to incorporate models and code and customize
  - Import and drag-and-drop build environments
  - Instrument, record, and export data

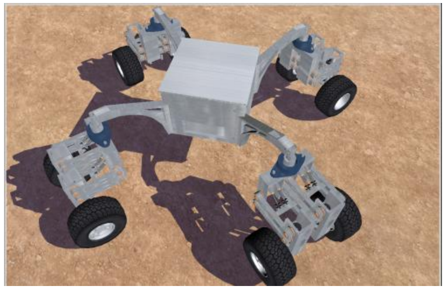
- **Developed by Quantum Signal in Saline, Michigan**

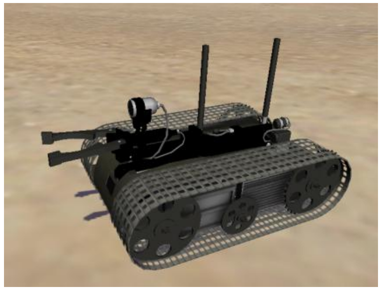
- **No-cost government and academic versions**
  - All source code available to government





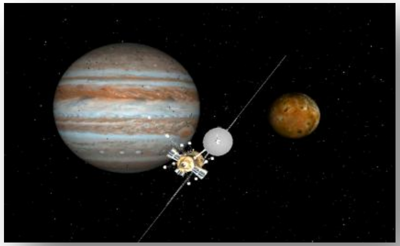
ANVEL Vehicles by Quantum Signal

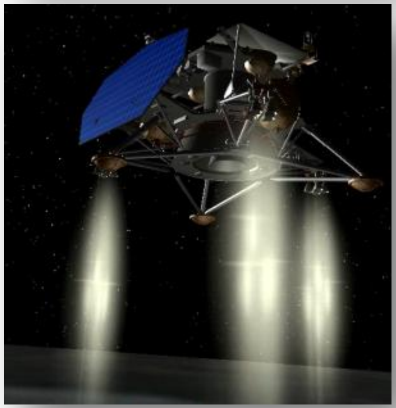


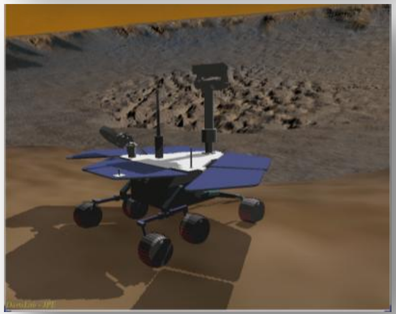


Rover Analysis, Modeling, and Simulation (ROAMS)

- **The JPL DARTS lab team has been involved in vehicle modeling and simulation for over 20 years**
- **Many key JPL/NASA missions require high-fidelity simulations**
  - Spacecraft missions (Cassini, MER, MSL)
  - Planetary rovers (Pathfinder, MER, MSL, research rovers)
- **The DARTS lab team created ROAMS for vehicle simulations of planetary rovers (http://dartslab.jpl.nasa.gov)**







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ROAMS Vehicles by NASA JPL

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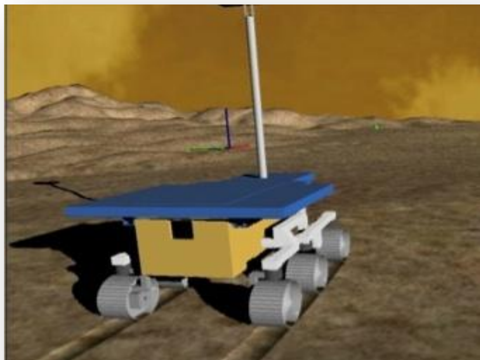
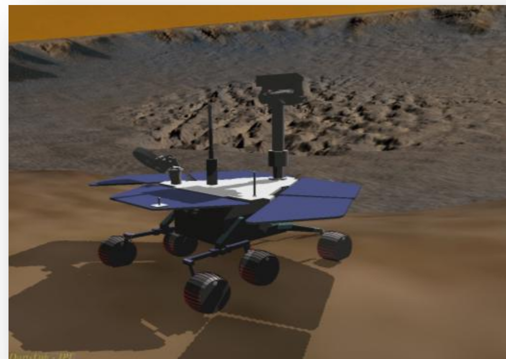
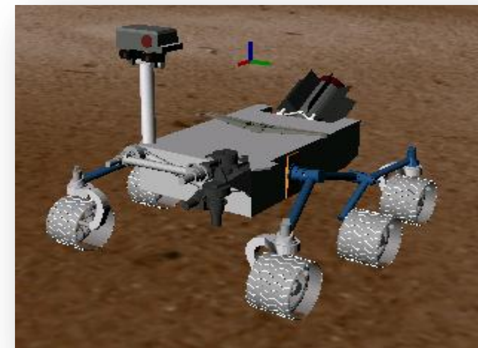
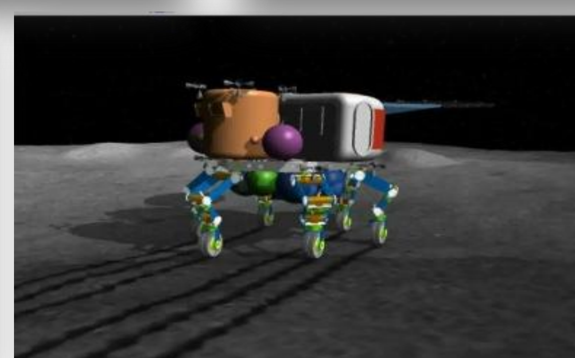








Benchmark Attributes

Platform Mobility

- Vehicle Modeling
- Terrain interaction
- Physics Engine
- Scenario Development

Autonomy

- Sensor Models
- Control Algorithm
- User Cognitive Model
- Shared Control Framework

Hardware / Software

- Compute Power
- Visualization

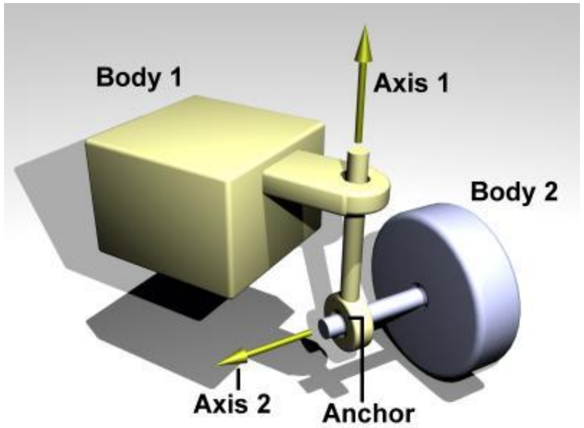
Benchmark: Vehicle Modeling

Benchmark Feature	ANVEL	ROAMS
Wheel Vehicle Modeling	Simplified	Yes
Tracked Vehicle Modeling	No	No
Suspension Modeling	Simplified	Detailed
Tire Modeling	Rigid Wheel/Tire Pacejka Slip Model	Rigid Wheel/Tire
Kinematic Joint Modeling	Limited: 4 Joint Types	Larger Library: 10+ Joints
Internal Force Modeling	Limited: Linear Spring/ Damper	Linear & Nonlinear Spring/ Damper
Collision Detection	Uses *OpenDE*	Uses *Bullet*
Contact Modeling	Hard Contacts: Constraints	Hard Contacts: Constraints Soft Contacts: Penalty
Scalability	No: $O(N^3)$	Yes: $O(N)$

Suspension Modeling Differences

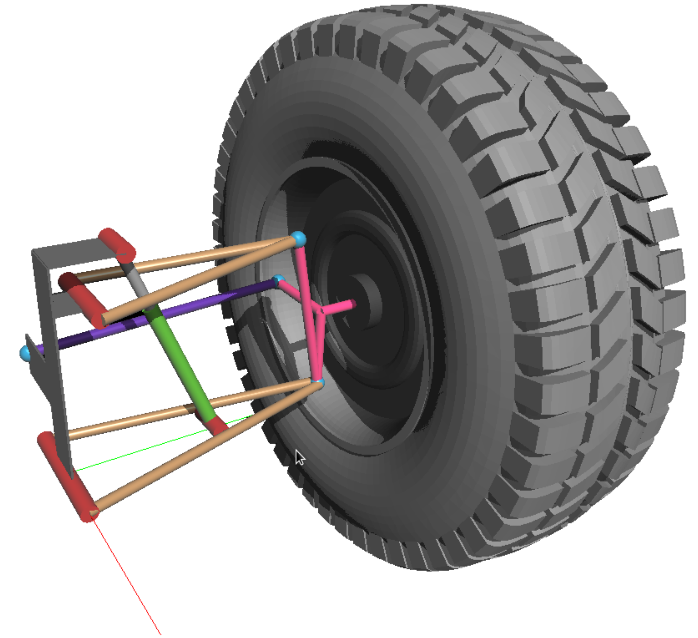
ANVEL: Simplified

- Only vertical suspension motion



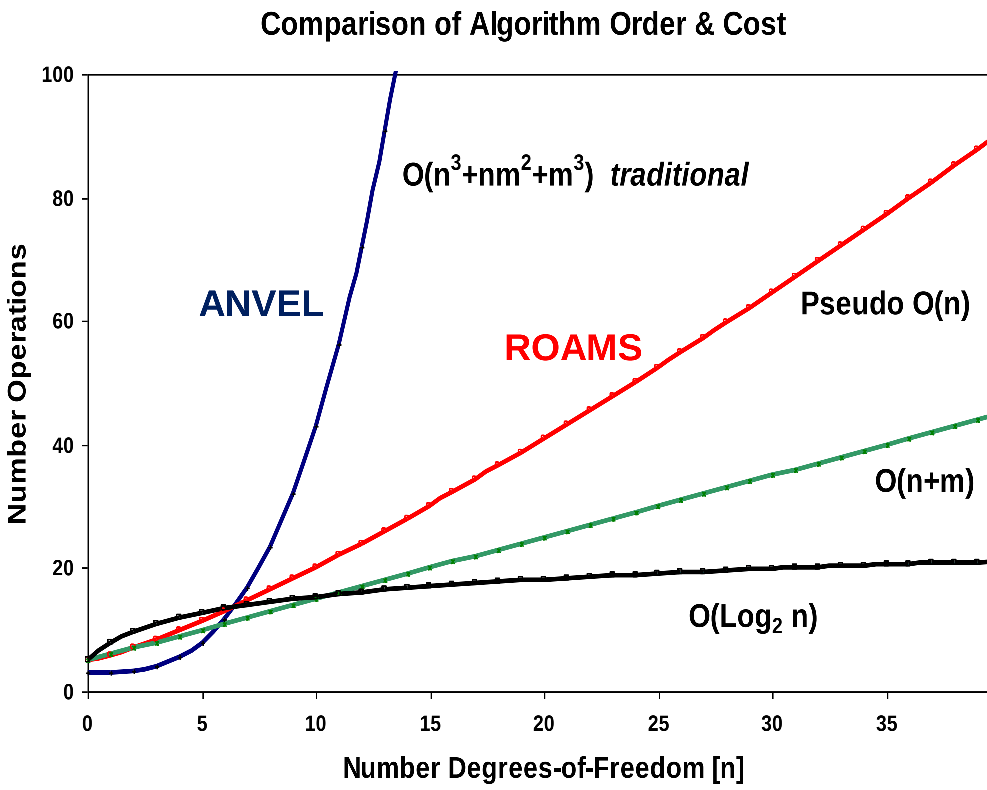
ROAMS: Realistic

- Detailed suspension model



Scalability

Compute Cost vs. Problem Size



Benchmark: Terrain Interaction

Benchmark Feature	ANVEL	ROAMS
On-Road Terrain (Rigid)	Uses *OpenDE Hard Contacts* Pacejka Slip Model	N/A for Planetary Missions
Off-Road Terrain (Deformable)	Bekker and Janosi-Hanamoto ERDC GCE Model	F_N: Hunt-Crossley Model F_T: Mohr-Coulomb Model

Benchmark: Scenario Development

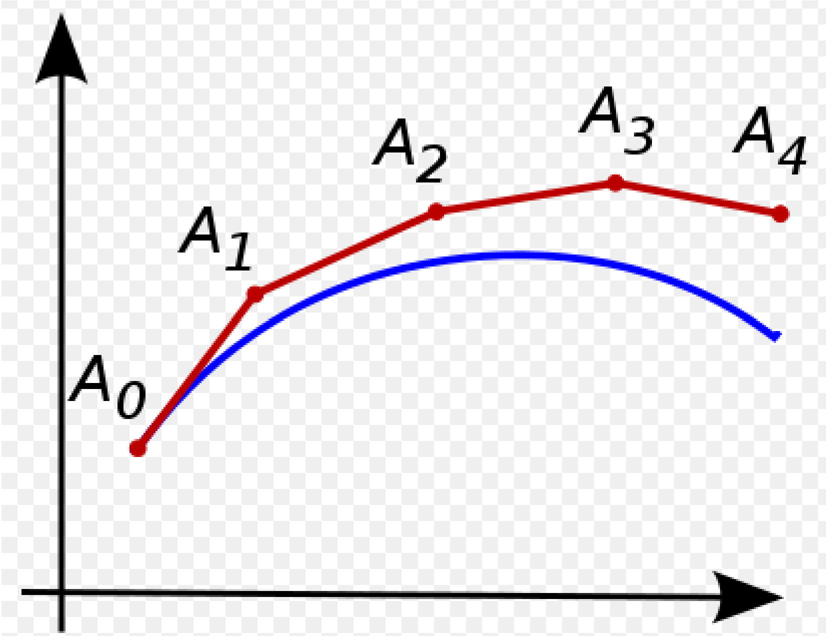
Benchmark Feature	ANVEL	ROAMS
Urban	Native or Import	*City Engine* Import
Off Road	Native or Import	Surface Height Map & Textures Import

Benchmark: Physics Engine

Benchmark Feature	ANVEL	ROAMS
Formulation	"Open Dynamics Engine" (*OpenDE)* Newton-Euler Equations Lagrange Multiplier Constraints DAE **$O(N^3)$ Interactive Solver**	Minimal Coordinates; Recursive; DE; **O(N)**; Constraint Embedding for Loops; Spatial Operator Algebra – No Mass Matrix Inversion
Integrator	Euler Algorithm Explicit: **Conditionally Stable**	*CVODE* from Lawrence Livermore Adams-Moulton Implicit Algorithm for Non-Stiff Systems, BDF Implicit for Stiff Systems: **Unconditionally Stable**
Integration Order	1	Variable: 1-5 for Stiff Systems 1-12 for Non-Stiff
Integration Step Size	Fixed	Variable
Simulation Fidelity	**Low: Good Enough for Gaming** **Not Accurate for Engineering**	**High: Required for NASA applications**
Simulation Speed Expected	Real Time	Real Time

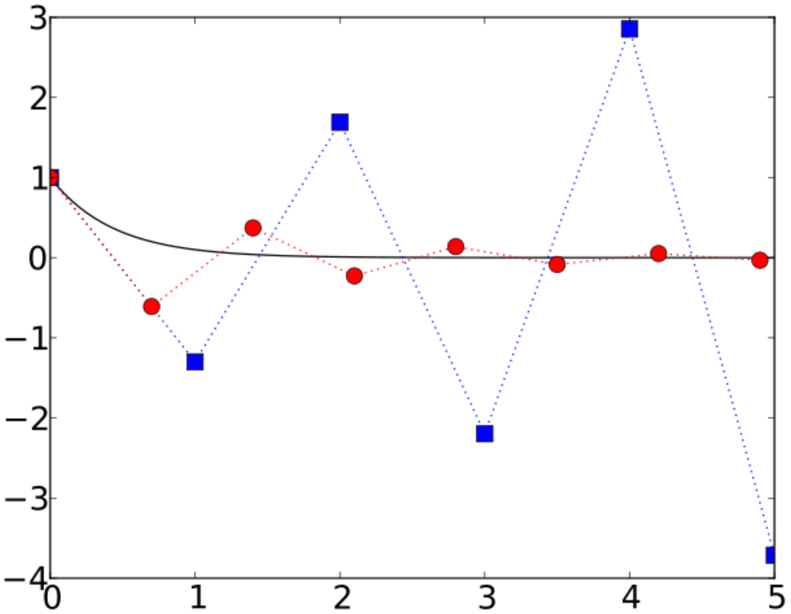
ANVEL: Euler Integrator

Accuracy



Blue: Exact solution
Red: Euler method

Stability



Black: Exact solution of y' = - 2.3 y
Blue: Euler method, step size = 1
Red: Euler method, step size = 0.7

ANVEL STABILITY

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Benchmark: Autonomy

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Benchmark Feature	ANVEL	ROAMS
Sensors	LIDAR, IMU, GPS, Camera	LIDAR, IMU, GPS, Camera, Wheel Encoders
Control Algorithm	Native Solution (PID?)	Open Loop Closed Loop: PID
Obstacle Avoidance	No	No
Dynamic Stability	No	No
User Cognitive Model	No	No
Shared Control	Joystick Interface: Yes M&S: No	Joystick Interface: Yes M&S: No

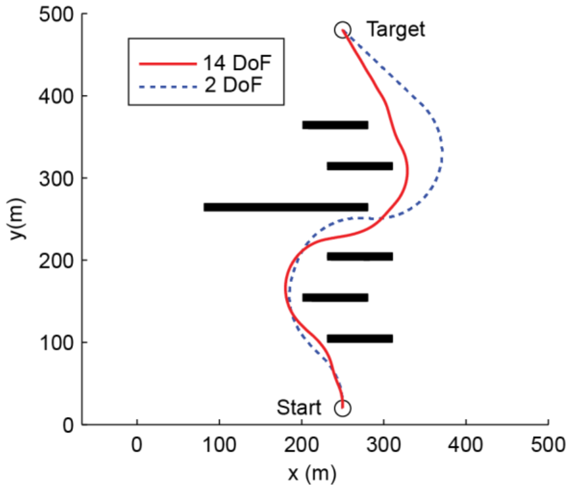
Benchmark: Hardware / Software

Benchmark Feature	ANVEL	ROAMS
Compute Power	**Desktop**	**Desktop**
OS	Linux, Windows	Linux
Ease of Use	GUI	GUI
Language	C++ and XML	C++ and Python
Usage Rights	Government Rights	**Government Owned**
Maintenance	Contractor	Government

Benchmark: Visualization

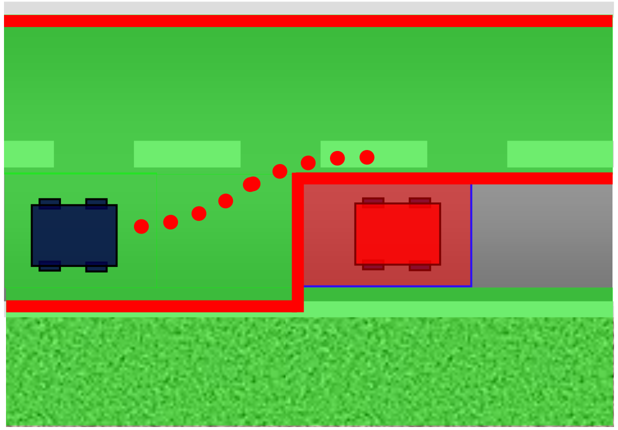
Benchmark Feature	ANVEL	ROAMS
Geometry Import	OBJ, 3DS, OGRE Mesh Formats	Vehicle: Most CAD Formats Terrain: Most DEM and Mesh
Rendering Engine	*OGRE*	*OGRE and GPU Shader*

Mobility Scenarios of Interest



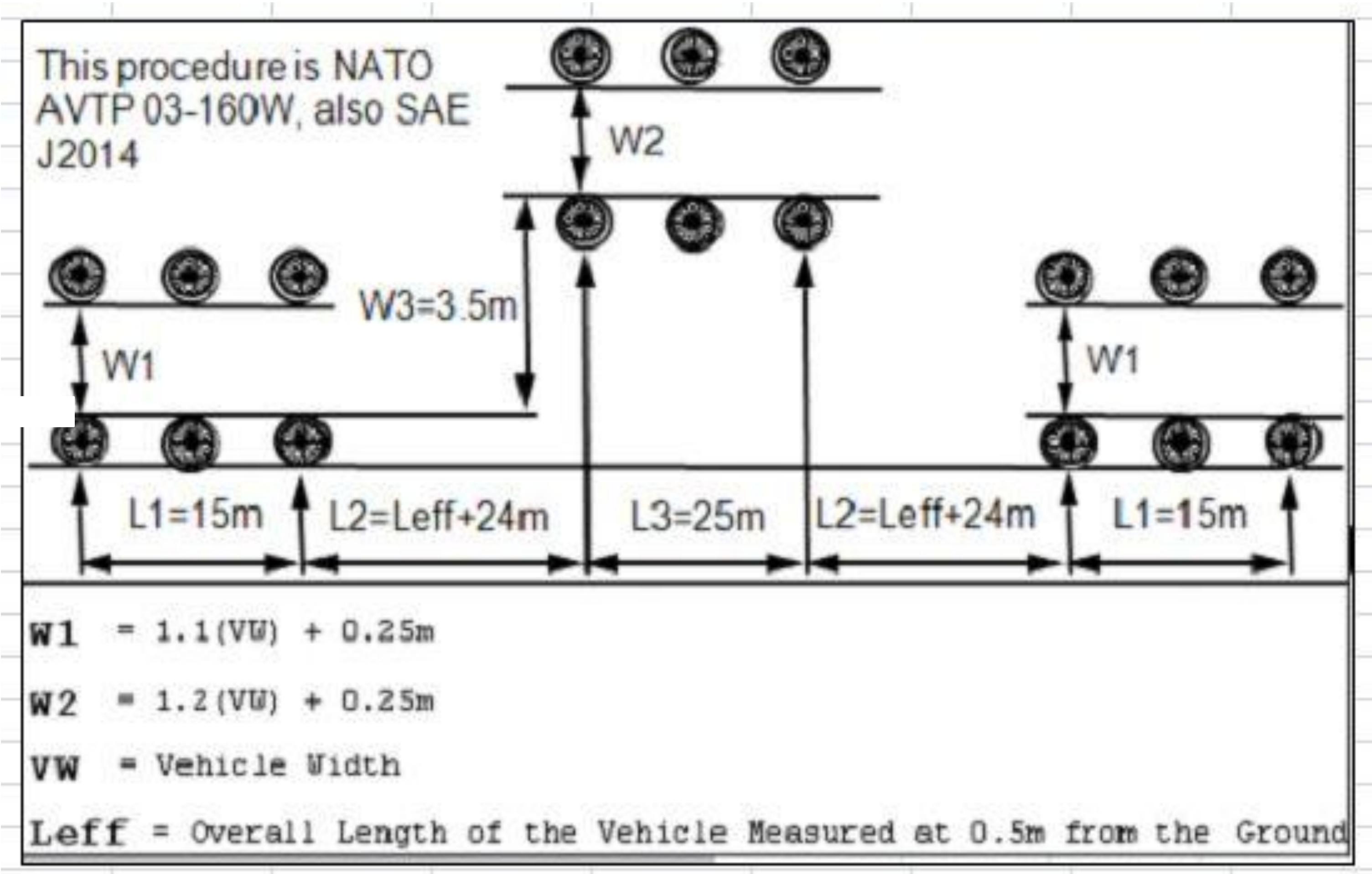
Urban Navigation

Double Lane Change



Off-Road Mobility

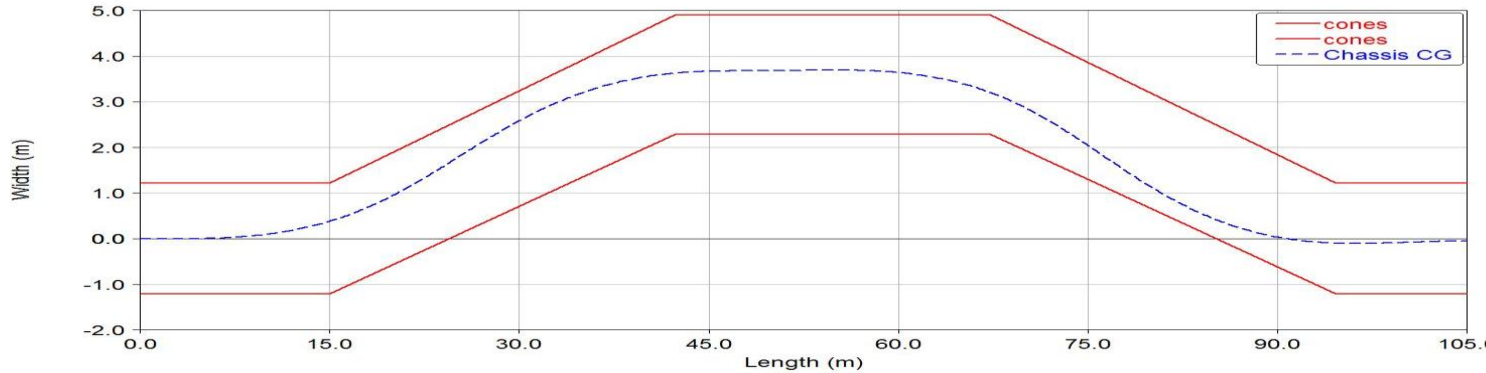
NATO Double Lane Change Maneuver



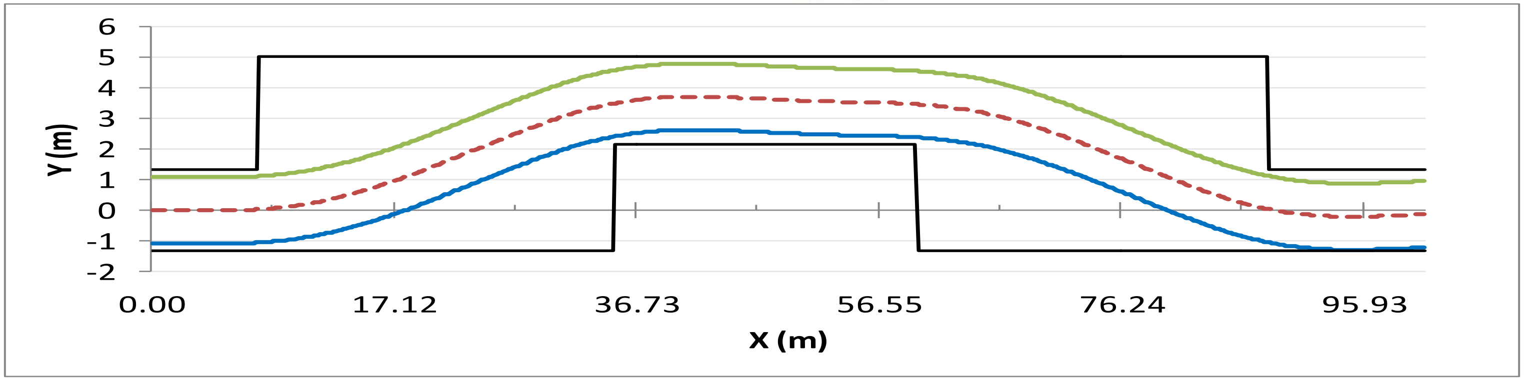
NATO Lane Change Test Course with Cones

Vehicle Path vs. NATO Course

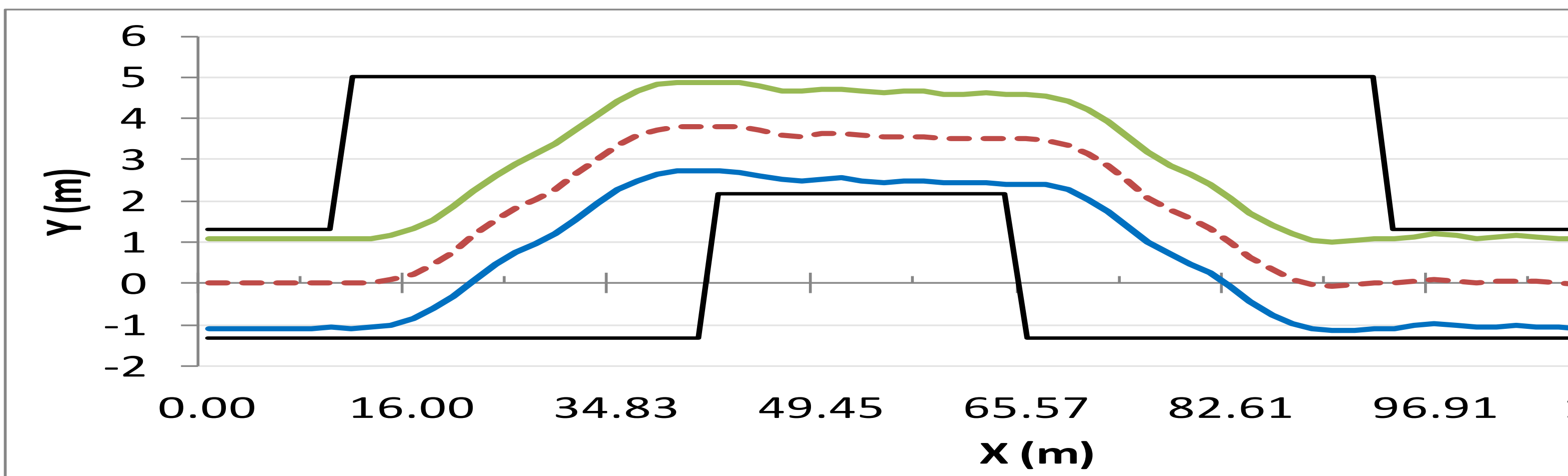
ADAMS



ROAMS



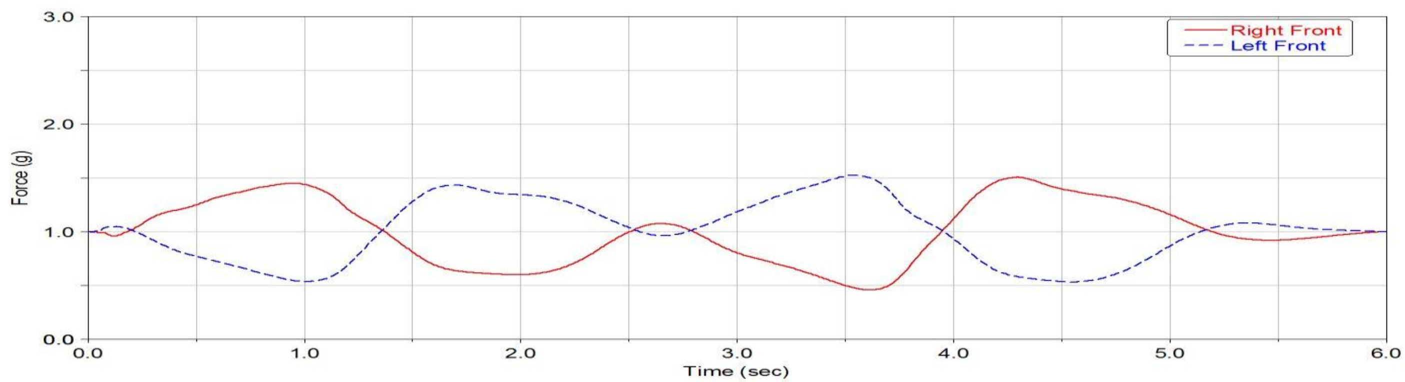
ANVEL



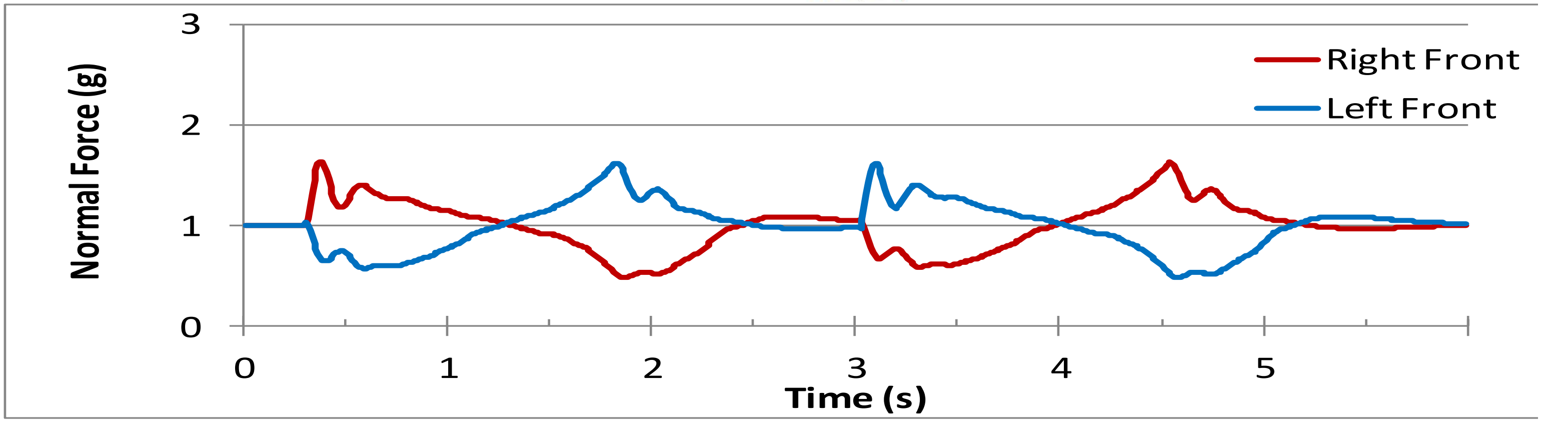
UNCLASSIFIED

Tire Normal Force @ Front

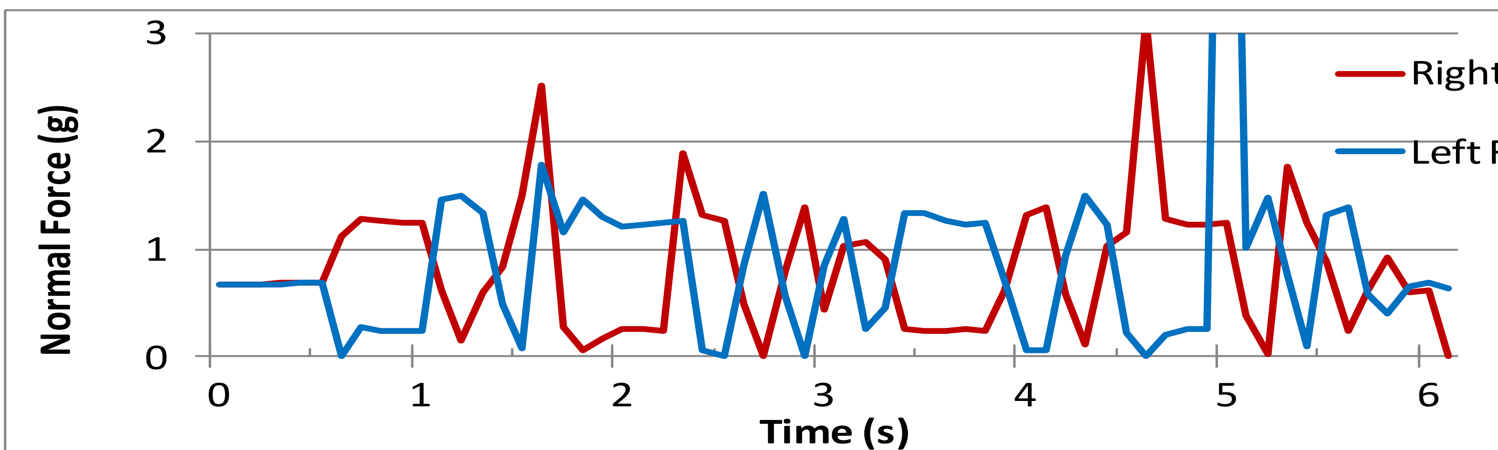
ADAMS



ROAMS

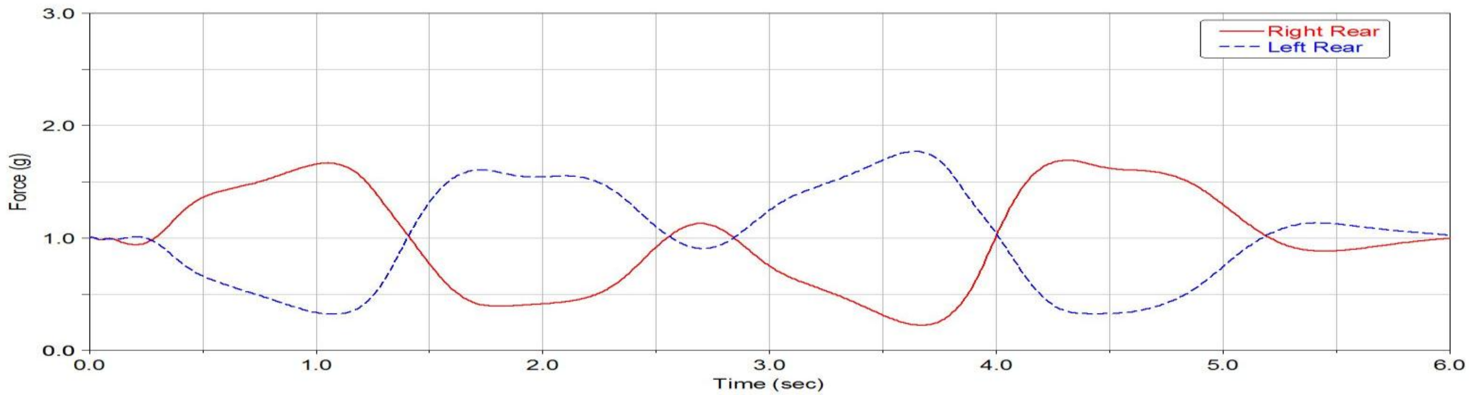


ANVEL

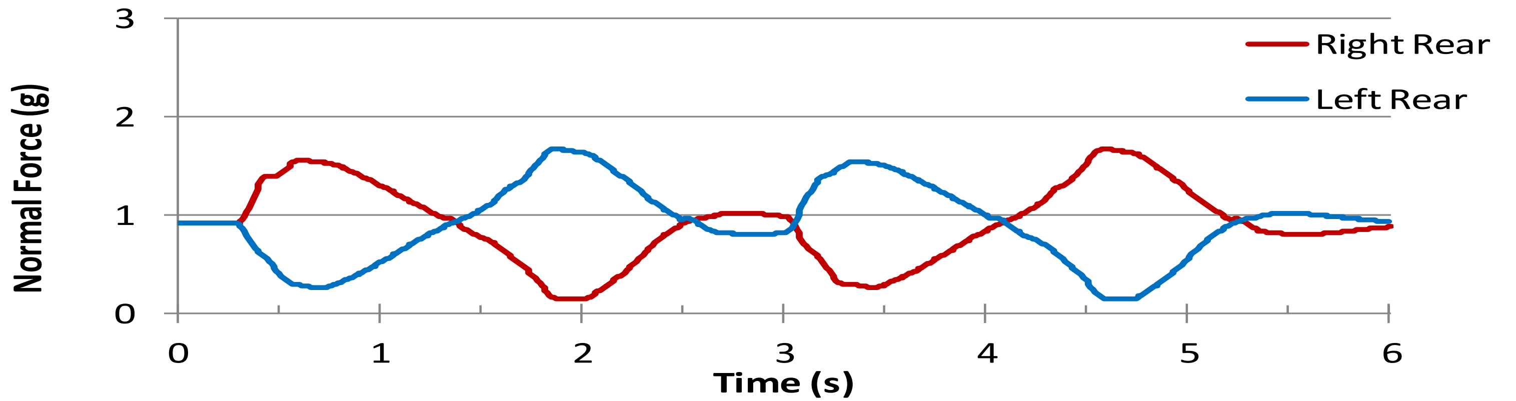


Tire Normal Force @ Rear

ADAMS



ROAMS



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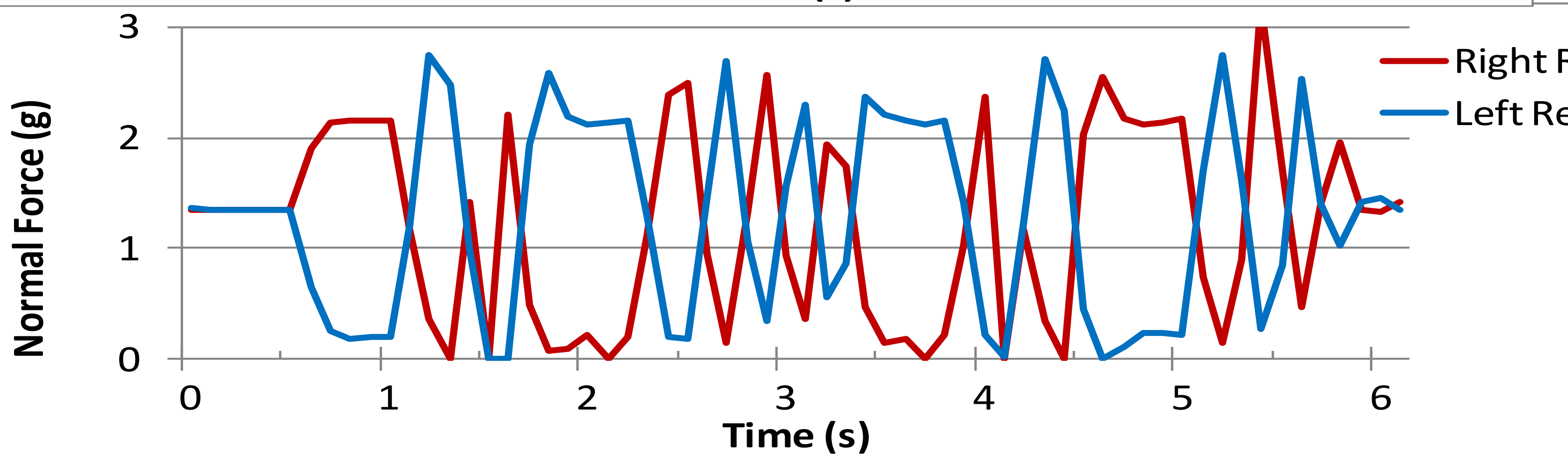
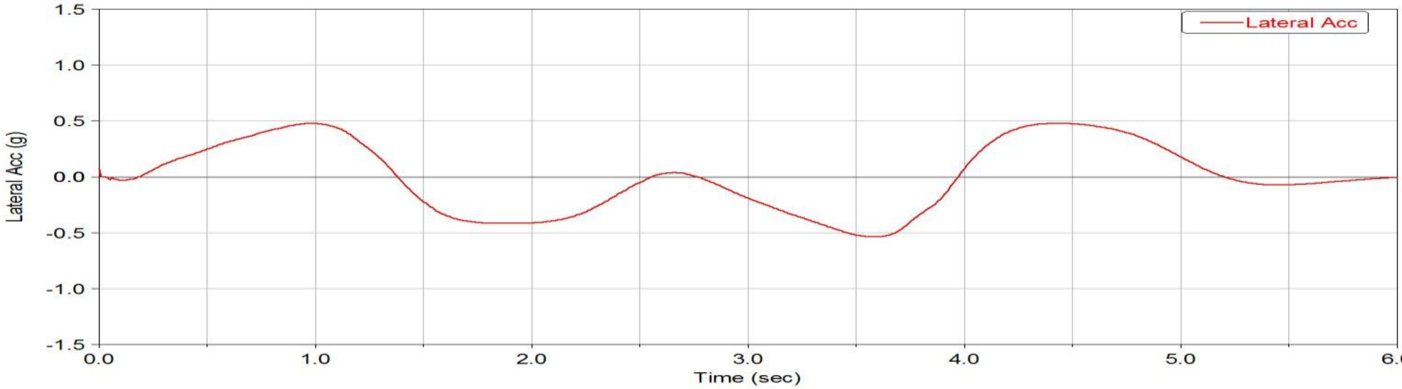


Lateral Acceleration

ADAMS



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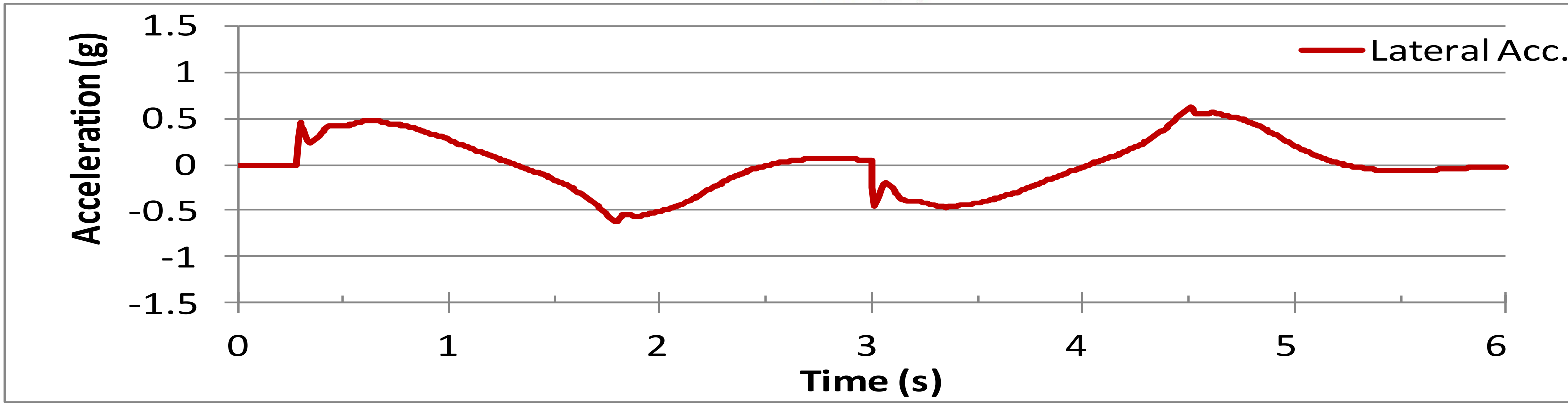

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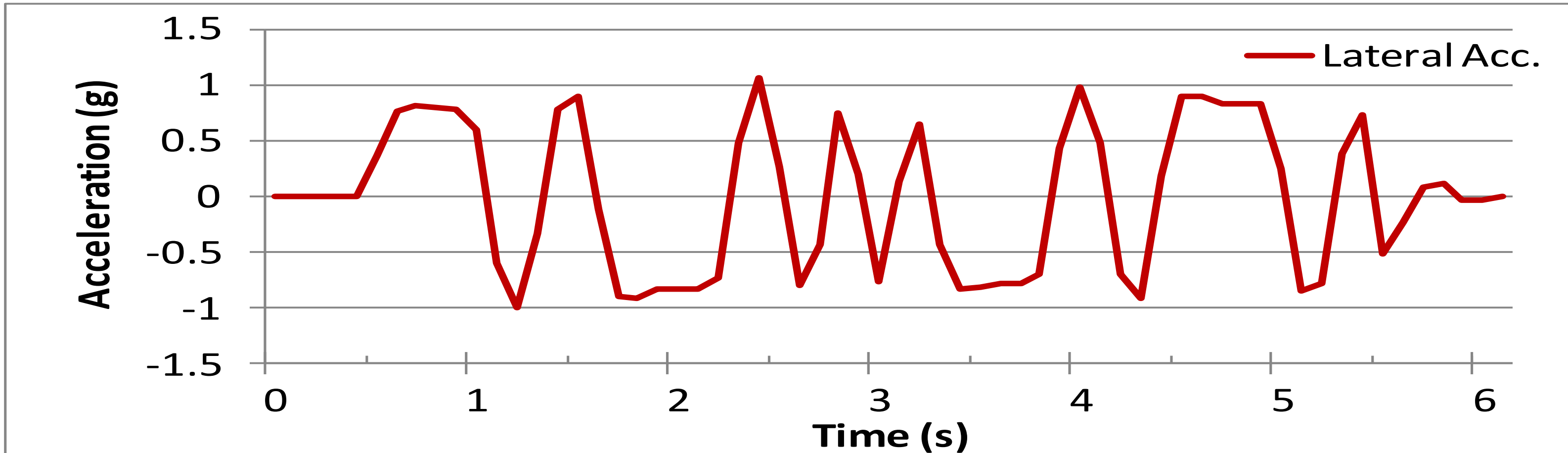
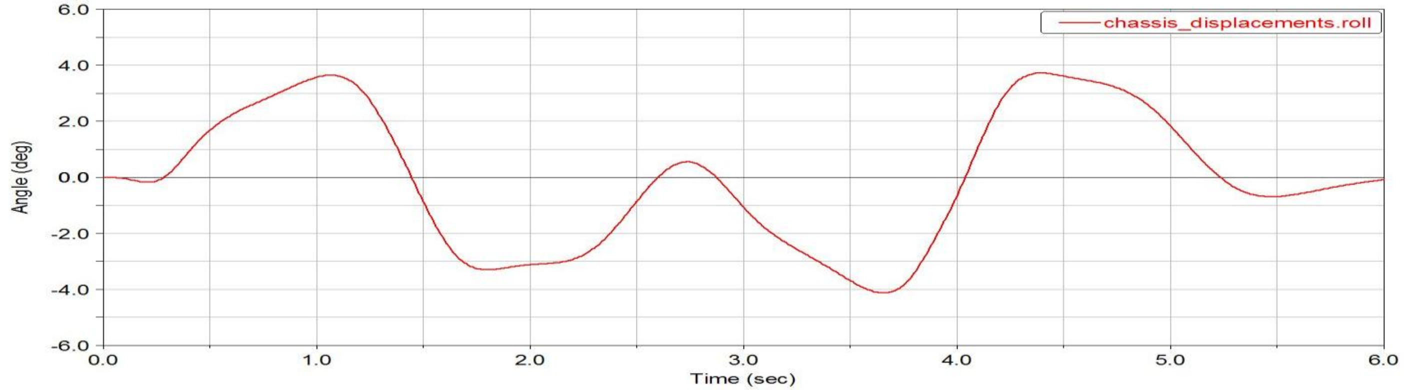


Roll Angle

ADAMS



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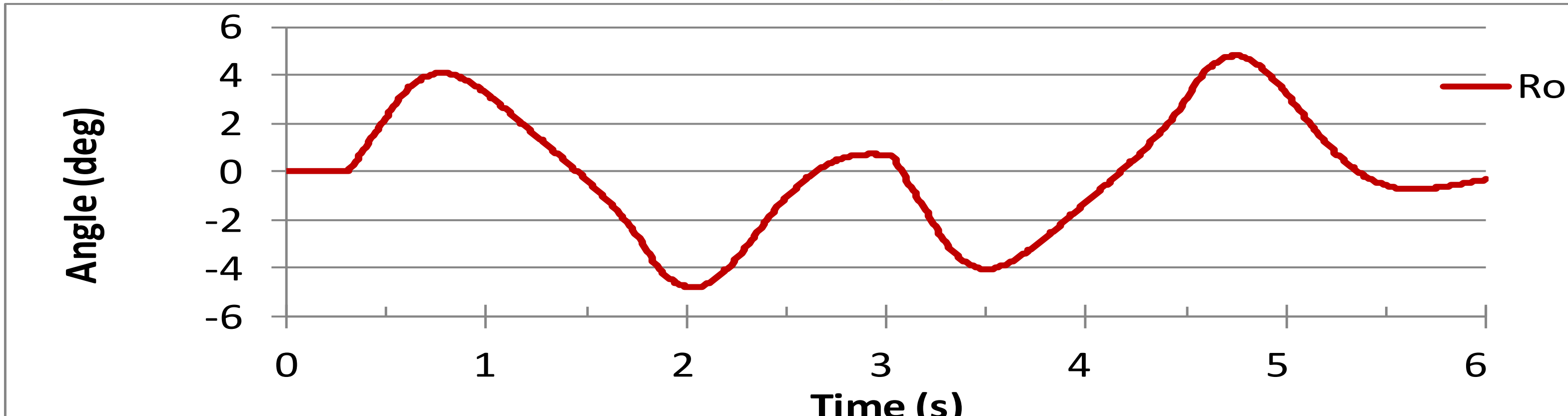

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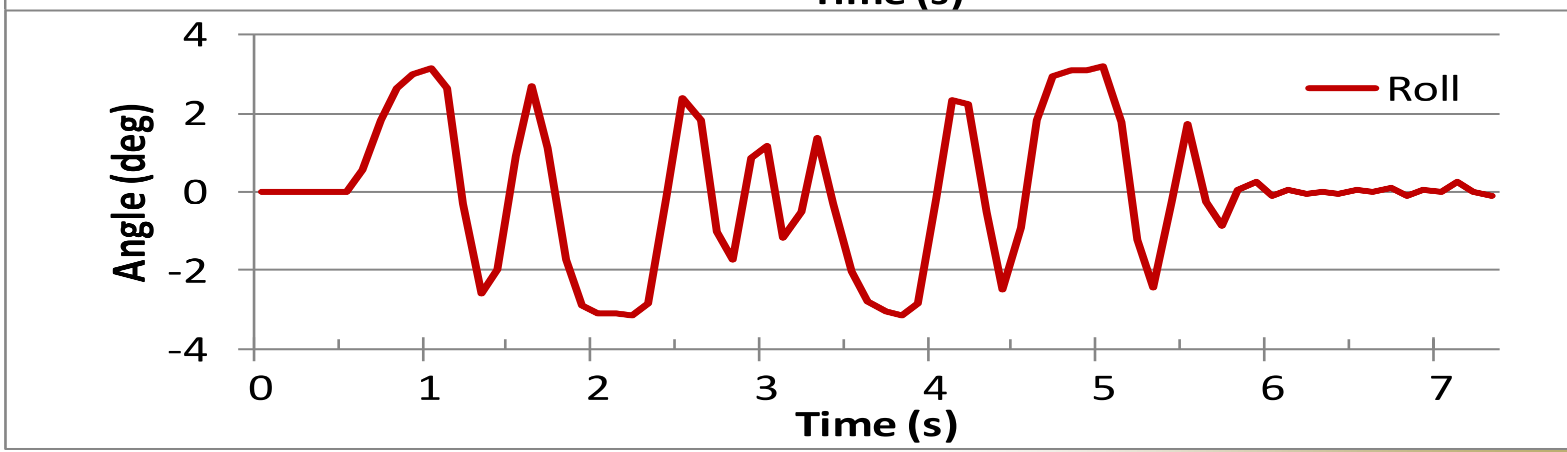
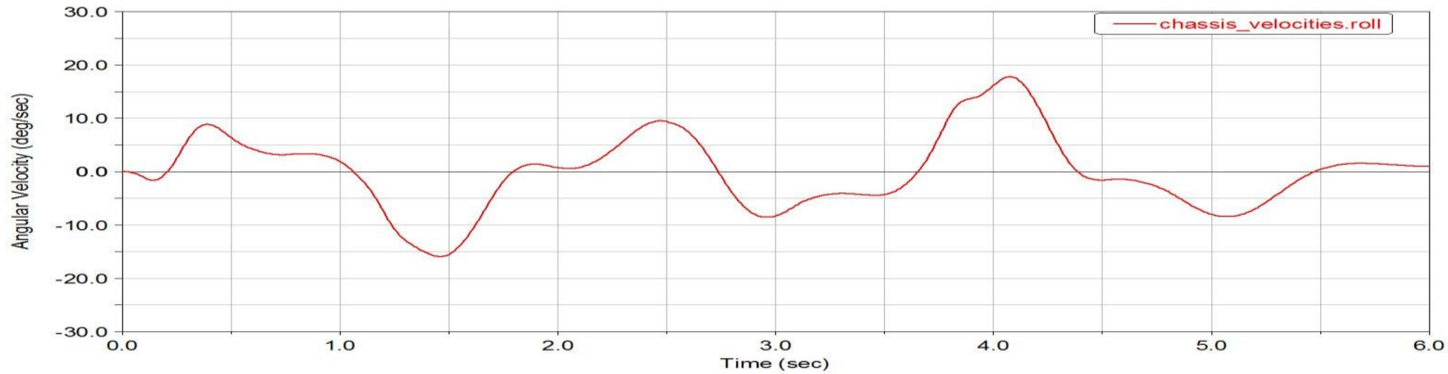


Roll Rate

ADAMS



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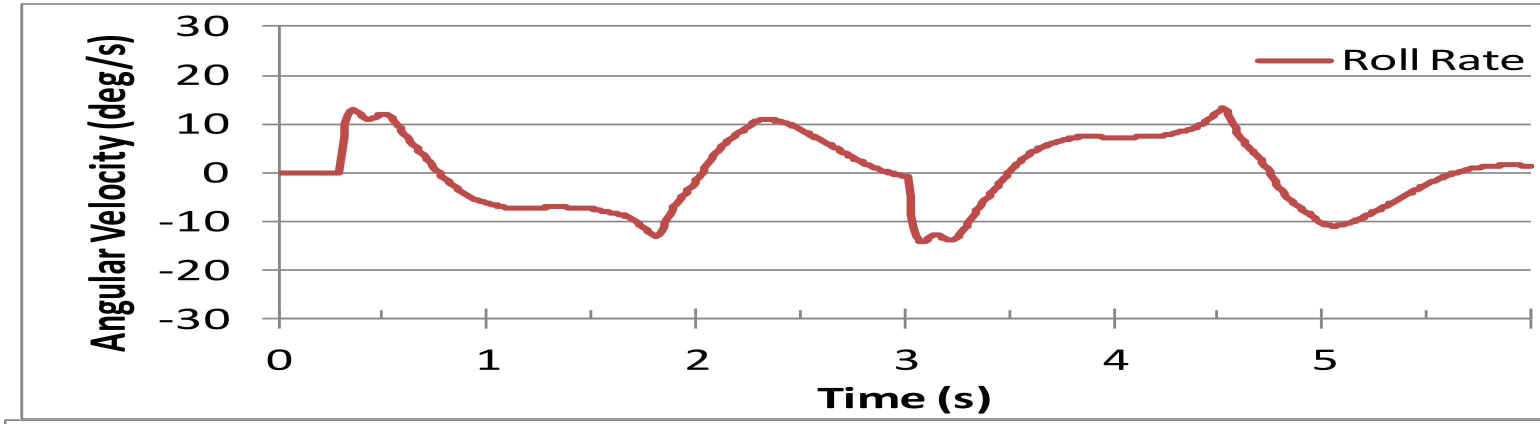

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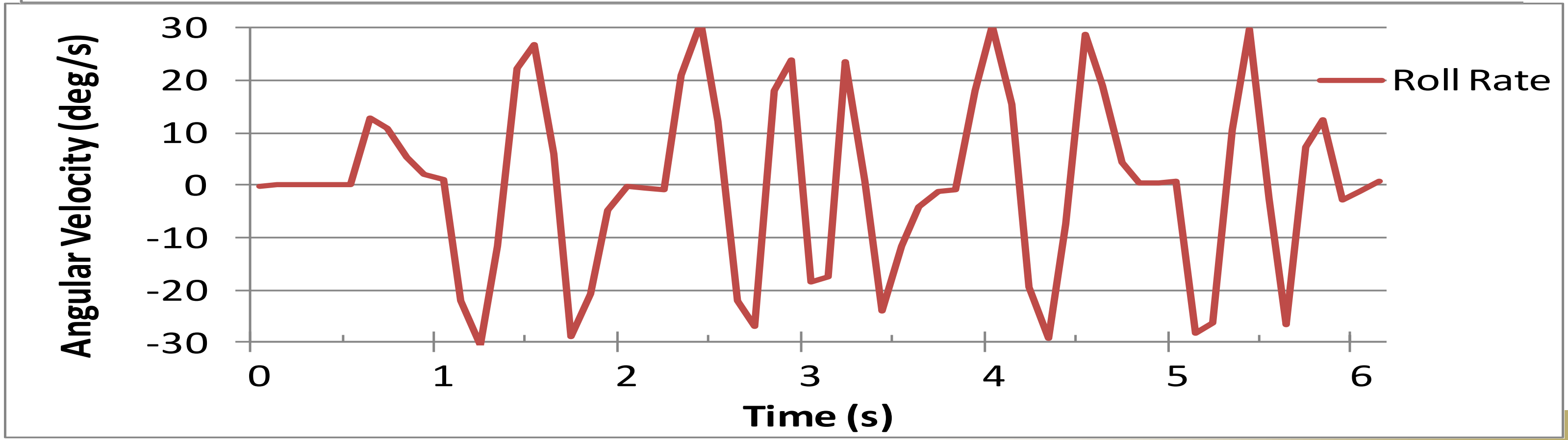
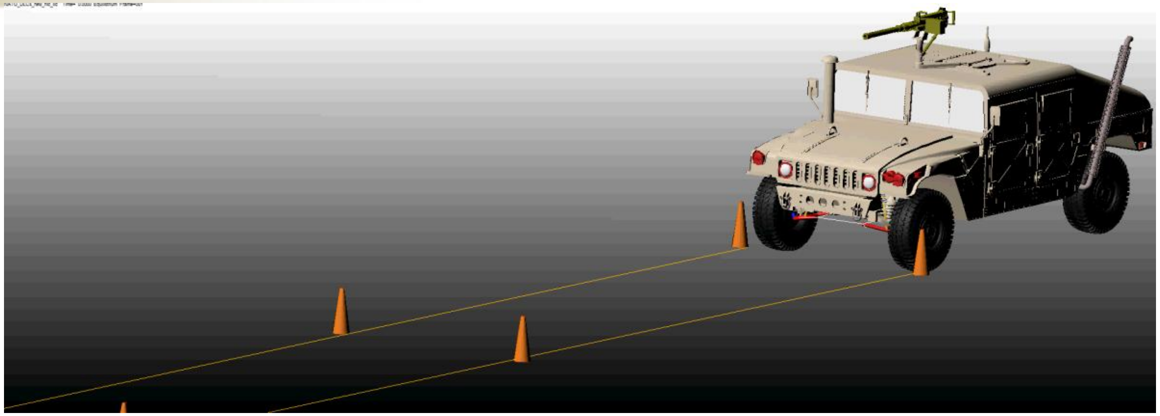


Animation

ADAMS



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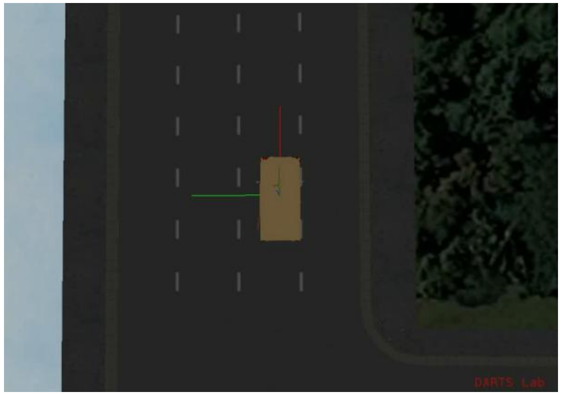
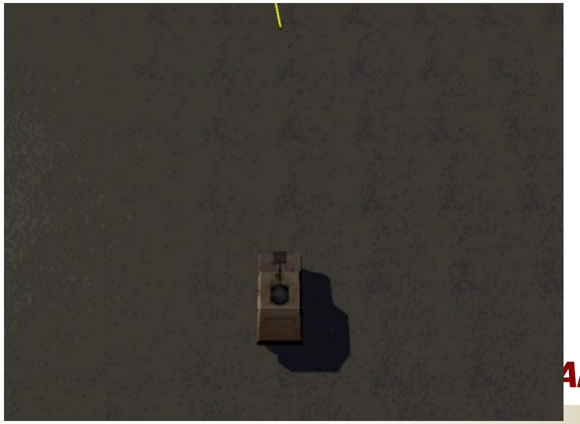


ANVEL



Simulation Results

Response		ADAMS		ANVEL		ROAMS	
		Max	Min	Max	Min	Max	Min
Tire Vertical Forces (g)	Left Front	1.5	0.5	10.0	0.0	1.6	0.5
	Right Front	1.5	0.5	3.1	0.0	1.6	0.5
	Left Rear	1.8	0.3	2.8	0.0	1.7	0.1
	Right Rear	1.7	0.2	3.2	0.0	1.7	0.1
Lateral Acceleration (g)		0.5	-0.5	1.1	-1.0	0.6	-0.6
Body Roll Angle (deg)		4.1	-3.7	3.2	-3.2	4.8	-4.8
Body Roll Rate (deg/s)		16.0	-17.8	31.1	-30.4	13.2	-14.4
CPU Time per Simulation Time (s/s)		8.8[a]		10.2[b]		3.4[c]	

a: ADAMS simulated with a maximum step size of 0.001 sec (variable step size integrator); Error tolerance 0.01

b: ANVEL is capable of real time simulation, however, with the default step size of 0.01 sec, the simulation was unstable and crashed. Step size reduced to 0.001 sec

c: ROAMS simulated with the default maximum step size of 0.01 sec (variable step size integrator); Error tolerances: rel 10^{-4}, abs 10^{-8}

Summary Results

- **M&S Features**
  - ANVEL offers intuitive user interface and is easy to generate models, but lacks necessary modeling components for accurate vehicle dynamic modeling
  - ROAMS offers all necessary modeling components and can model suspensions
- **M&S Capabilities**
  - ANVEL has an unstable and inaccurate dynamics solver which was not designed for engineering applications
  - ROAMS has an advanced dynamics solver that is inherently stable, accurate, and efficient for near real time applications
  - Both software lack high speed obstacle avoidance algorithm
  - ADAMS is an off-line (non real-time) high fidelity mobility M&S tool, the gold standard to compare to

Conclusions

- **Transition**
  - Both ANVEL and ROAMS have been transitioned to TARDEC including source code
- **Recommendation**
  - NASA JPL software ROAMS is recommended for further consideration as UGV Mobility M&S tool for TARDEC
- **Current Development / Next Steps**
  - Develop and integrate within ROAMS (JPL and TARDEC)
    - Human cognitive model (TARDEC)
    - High speed obstacle avoidance algorithm (UM/ARC)
    - Shared control algorithm (MIT)
    - Terramechanics model (TARDEC)
  - Advanced training in ROAMS software
  - Develop templates for suspensions, terrains, scenarios, etc.
  - Investigate effect of latency and autonomy on mobility
  - Understand Extreme Mobility